THE SCATTERING OF POSITIVE IONS FROM A PLATINUM SURFACE

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Abstract

The velocity and intensity of positive ions scattered at various angles from a metal surface have been measured by allowing the ions scattered from a heated platinum target to pass through slits into the electric and magnetic analysing fields of a positive ray box. The source, oxide catalyst emitting potassium, caesium, or lithium ions, could be rotated round the target, so that the latter could be bombarded from any angle. When the target was brought to a red heat the intensity of scattering was markedly increased, presumably because of the removal of a layer of adsorbed gas.

Velocity distribution. With a homogeneous initial beam the ions scattered at a given angle are nearly homogeneous in velocity. But the energy retained by the ions varies continuously with the angle of incidence, rising from 20 percent of the initial energy to over 80 percent as grazing incidence is approached. The velocity of ions scattered from a cold target on which an adsorbed layer has formed is much less, the energy retained rising to only 40 percent of the initial energy near grazing incidence.

Angle distribution. A separate apparatus was used to explore the intensity of scattering in all directions, by means of a collector which could be rotated around the source. For angles of incidence near the normal the intensity of scattering is very small or even zero, but increases with increasing angle of incidence. The most intense scattering takes place in a forward direction, the number of particles which suffer large deflections being small. Thus for a fixed angle of incidence the number of particles scattered in a direction normal to the target is very small or even zero, but increases steadily with increasing angle of reflection.

Critical energy. The intensity of scattering varies greatly with the energy of the incident ions, rising to a sharp maximum at about 40 volts. This critical energy for intense scattering is found to be the same for caesium, potasium, and lithium ions.

THE scattering from solid surfaces of particles of small momentum has been investigated by Davisson with Kunsman and Germer[1] who studied electrons, and by Ellett and Olson[2] who examined slow atoms of cadmium, mercury, sodium and hydrogen. In the experiments to be described here the scattering of particles of comparatively high momentum has been examined.

In an apparatus set up to investigate ionization of gases by fast positive ions it was found impossible to get rid of primary ions, which, after being scattered about from the metal sheath which lined the walls of the tube, found their way into the positive ray box intended for the analysis of the products of ionization. The original experiment was therefore postponed, and a target set up to examine this intense scattering. The velocities and distribution of alkali ions scattered from a heated strip of platinum foil have been measured by allowing the scattered ions to pass through slits into the electric and magnetic fields of a positive ray box of the Dempster type as

[1] Davisson and Kunsman, Phys. Rev. **22,** 242 (1923); Davisson and Germer, Phys. Rev. **30,** p. 705 (1927).

[2] Ellett and Olson, Phys. Rev. **31,** p. 312 (1928).

used by Smyth, Brasefield and others. While these experiments were in progress some work on the scattering of positive ions was reported by G. E. Read,[3] whose results differed in many points from the results which the writer had obtained. Read did not employ magnetic analysis to determine the velocity distribution of the ions, but allowed the scattered ions to impinge on a metal plate which could be rotated around the target. A simple apparatus, similar to his but with greater resolving power, was accordingly set up to investigate the points of difference. The results obtained are in agreement with those found with the positive ray box.

Apparatus

The first apparatus is shown in Fig. 1. An accelerating voltage applied between the catalyst oxide source, O, and the surrounding copper box, B, directed a stream of positive ions at the target T. The source and box were

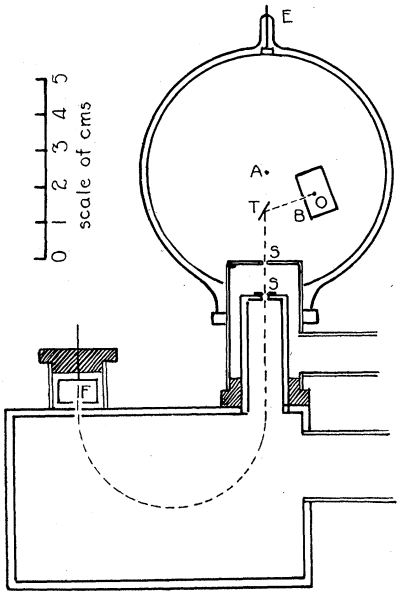

Fig. 1. Diagram of first apparatus.

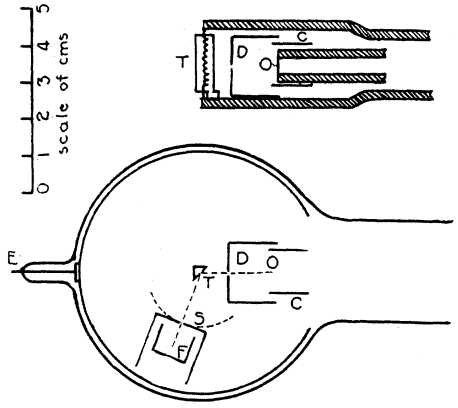

Fig. 2. Diagram of a second apparatu s.

mounted on a ground glass joint so that the target could be bombarded from any angle. It should be noted, however, that for a given orientation of the target the angle of reflection could not be varied. The ions scattered vertically downwards passed through the slits S, S into the positive ray box, where the magnetic field could be made to bring them around into the Faraday cylinder F, which was connected to a Compton electrometer.

The source of ions was a catalyst oxide of the type used by Kunsman,[4] containing a small amount of either potassium, lithium, or caesium and de-

[3] Read, Phys. Rev. **31**, p. 155 (1928).

[4] Kunsman, Jour. of Phys. Chem. **30**, 525 (1926); Barton, Harnwell, and Kunsman, Phys. Rev. **27**, 749 (1926).

posited on a platinum filament, which was held taut by a small molybdenum spring. The glass tube was lined with platinum foil, supported by the electrode E, which was put in electrical contact with the upper slit of the positive ray box. The target, a strip of platinum foil, through which a heating current could be passed, was held taut by a steel spring which took up the extension of the strip when the latter was brought to a red heat. The stray field of the electromagnet was compensated by a current passed through coils wound round the experimental tube.

The second apparatus is shown in Fig. 2. The face of the nickel drum D was pierced by a hole of 0.4 mm radius. At 12 mm from this was the source O, a speck of Kunsman oxide catalyst, on a short platinum filament. An accelerating voltage applied between the source and the drum directed a stream of ions at the target T; this was a piece of platinum welded to a nickel tube of triangular cross-section down the center of which ran a tungsten heating spiral. The source, drum and target were all mounted on one four-lead stem that could turn in a ground glass joint around ODT as axis. The drum, the target, and one end of the tungsten heating spiral were all welded to the same lead. Welded to one of the leads which supported the source was an additional cylinder C which protected the source from stray fields from the leads. The nickel parts were all outgassed by means of the induction furnace before assembling.

The collector was a small nickel box F, enclosed in a shield S, the front face of which was pierced by a circular hole of 0.6 mm radius. The lead supporting the collector was connected to the electrometer and was surrounded by a nickel tube, to which the shield S was welded. The glass tube was lined with a platinum foil supported by the electrode E; both this and the shield S were maintained at earth potential.

The collector could be moved around the target about a horizontal axis by turning the ground stem on which it was mounted. To explore the particles scattered in all directions we require to rotate the collector about another axis, at right angles to this first one. Since the initial beam was directed down the axis of the other ground joint, on which the target too was rigidly mounted, it is clear that turning this joint is exactly equivalent to moving the collector around the target about a vertical axis. In this way the whole hemisphere may be explored for a given angle of incidence, in contrast to the first apparatus.

An important plane is that which contains the initial beam and the normal to the target at the bombarded point. For if the beam of ions were a beam of light, the reflected beam would always lie in this plane, which we may call the meridian plane. It is clear that the collected beam lies in this plane when the target is parallel to the horizontal axis around which the collector moves. In the previous tube the collected beam was kept permanently in this plane, but in this second apparatus the collected beam could be in any plane passing through the direction of the incident beam.

Procedure and Results

Several results emerged almost as soon as the work started. In the first place, with a homogeneous initial beam the ions scattered at a given angle are nearly homogeneous in velocity, but this velocity retained by the ions varies continuously with the angle of incidence. In the second place, both the number of ions scattered and the proportion of the velocity retained by them are decidedly greater when the target is heated, but are independent of the temperature of the target when it is at least red hot. Presumably this results from the removal of a layer of adsorbed gas (e.g. grease vapour), which re-forms in a few minutes on allowing the target to cool, as described later.

The experiments which we will now describe in detail were taken with a heated target unless otherwise specified. All the curves shown in the diagrams in this paper were taken with the first apparatus, excepting those in Figs. 7 and 8.

With 1.0 ampere exciting current flowing through the coils of the magnet potassium ions of 65 volts energy are bent around by the magnetic field to enter the Faraday cylinder. The velocity distribution of the scattered ions is determined by finding how many volts applied between the slits S, S of the positive ray box are required to bring up the energy of the scattered ions to 65 volts. Thus for example when the voltage applied between the slits was 22 volts, the rate of deflection of the electrometer gave the number of particles which were scattered at the selected angle with 43 volts energy. (The velocities of fast ions could be determined by using a retarding instead of an accelerating field.) In any one determination of velocity distribution the following conditions were kept constant: A. Type of ion; B. Condition of target; C. Velocity of incident beam; D. Angle of incidence; E. Angle of reflection (for ions collected); F. Angle from the meridian (for ions collected).

The *velocity distribution* is found always to be a sharp peak, showing that the ions coming off at a given angle are nearly homogeneous in velocity. On comparing these peaks (Fig. 3) with peaks taken with the initial beam fired directly at the slits, it is found that they are but little wider, showing that the number of ions differing from the most probable velocity by more than one or two volts is small.

Change of velocity distribution with angle of incidence. If all the above conditions are kept constant except the angle of incidence, and the velocity-distribution is determined for various angles of incidence, a group of sharp peaks is obtained such as Fig. 3.

It is clear that the ions scattered at the selected angles differ not only in intensity but also in energy. The energy of the incident ions was 35 volts. The peak taken for incidence at 84° from the normal lies at 34 volts, so that the energy of its ions is $(65-34)=31$ volts. The peak taken at 44° incidence lies at 53 volts, hence its energy is at $(65-53)=12$ volts; i.e. the ions have lost about 23 volts, yet the peak is very little wider than the other in which the ions have lost 4 volts.

These energies of the scattered ions are plotted in Fig. 4, together with similar curves for other initial speeds, but all for the same selected angle of reflection. The points plotted for initial energies of 60 volts and 25 volts were derived from families of peaks similar to those shown in Fig. 3. In the case of 60 volt ions it will be seen that peaks were found in which the ions retained more than 50 volts or less than 10 volts. Yet such a large loss of energy as 50 volts is not accompanied by a great increase in the width of the peak; if the most probable energy retained by the ions is ten volts,

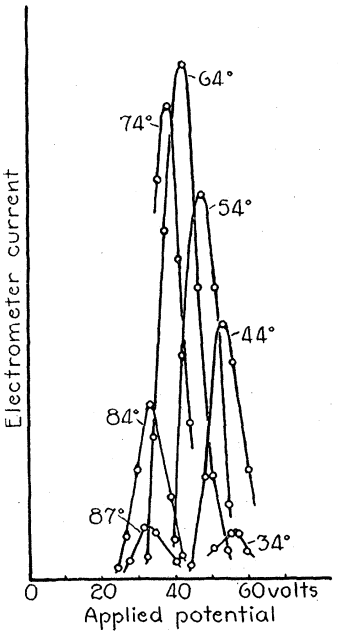

Fig. 3. Abscissas are volts applied between the slits of the positive ray box. Ordinates are intensity in arbitrary units. Initial energy of potassium ions was 35 volts. The selected angle of reflection was 66° from the normal.

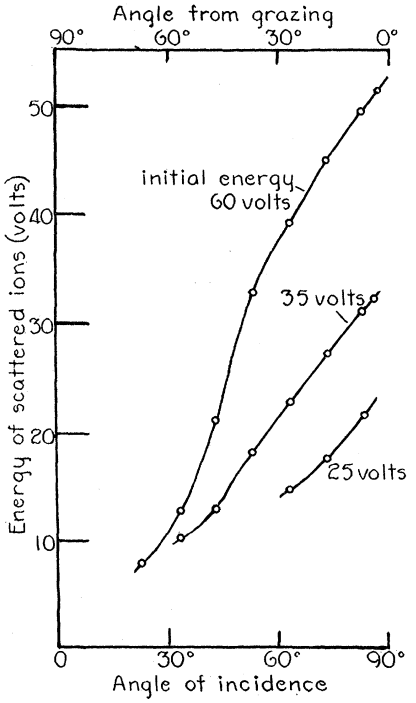

Fig. 4. Ordinates give the most probable energy of the scattered ions. Abscissae are angles of incidence. Selected angle of reflection was 66° from the normal.

most of the particles will lie in the range 10 ± 4 volts, having lost 50 ± 4 volts of energy.

Similar curves have been taken with ions of energies too great to be shown in Fig. 4. Curves almost identical with these have also been taken with lithium ions.

Variation of intensity with angle of incidence. The slits of the positive ray box, the upper 0.2 mm and the lower 0.4 mm wide, defined a narrow wedge-shaped volume, from which alone particles could reach the box. The

target was set accurately across this narrow solid angle by turning the ground-glass joint on which it was mounted, and whose axis was at A, Fig. 1. The orientation of the target was determined by introducing a pea-lamp into the positive ray box; the light reflected from the target formed an image of the slit on the copper box, B.

The incident beam was wide, and was intended to flood the target uniformly. The target was wide, but only a strip of width d, subtended by the slits, is operative. The width d subtends an angle ω at the source (Fig. 5), which varies from a maximum at normal incidence to zero at edge-on incidence. The angle ω is proportional to the cosine of the angle of incidence, and if the intensity of scattering were independent of the angle of incidence, the measured intensity would be proportional to this quantity, being a maximum at normal incidence.

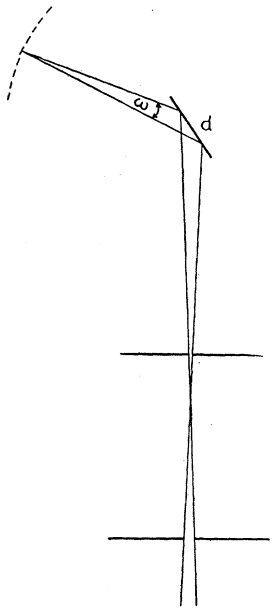

Fig. 5.

Instead of this, the intensity of scattering is found to be very low when the angle of incidence approaches normal.[5] Thus the observed intensity of scattering is a maximum for some intermediate angle of incidence, passing towards zero both for normal incidence and (by necessity) for edge-on incidence as ω tends to zero. This is shown by any family of peaks such as Fig. 3. The intensity obtained from these and similar peaks is plotted in Fig. 6 where each point represents the area of such a peak. The maximum occurs approximately at the specular angle, but we shall see that this is fortuitous. The question at once arises as to whether the observed decrease towards zero as edge-on incidence is approached is due to a factual decrease in the intensity of scattering, or whether it is due entirely to the decrease of ω. If we divide the intensity at each point by the corresponding value of ω, we find that, so far from decreasing, the curve continues to rise as edge-on incidence is approached. This means that the smaller the deflection (at the target) which the ions have suffered the more plentiful they are, since on increasing the angle of incidence the particles scattered at the selected angle have been deviated less. But the deduction of this result is not conclusive, since the rate at which the observed intensity falls to zero at edge-on incidence must depend on the finite width of the source, etc.

Variation with angle of reflection. The angle of reflection of the collected beam for which the curves in Fig. 6 were taken was 66° from the normal, (angle from grazing 24°). Now if reflection of the ions were approximately

[5] In studying the electron emission from metals under slow positive ray bombardment Jackson (Phys. Rev. **28**, 524, 1926) found that the intensity of reflection of potassium ions from various metals is for normal incidence "certainly less than 2 percent and may be zero."

specular, as reported by Read, we should expect to obtain for 66° incidence a smaller intensity, if we set the target to give some selected angle of reflection other than 66°. On the contrary, it was found that 75° reflection with 66° incidence gave a greater intensity than before, again suggesting that the particles are scattered in a forward direction.

To investigate this the second apparatus with movable collector was set up, as described above. The type of intensity curve for fixed incidence but varying angle of reflection as the collector was moved around the target in the meridian plane, is shown in Fig. 7. The scattered ions are found to be scattered in a forward direction in agreement with the results obtained with the previous apparatus. A similar curve was obtained with lithium ions.

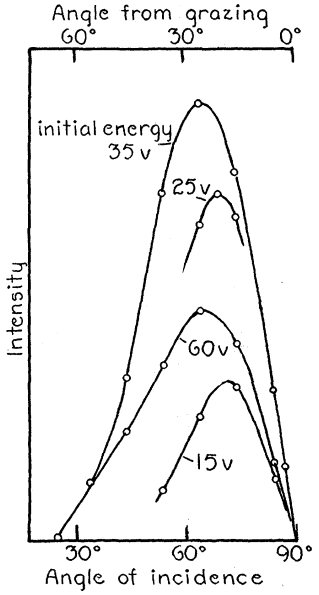

Fig. 6. Selected angle of reflection 66°.

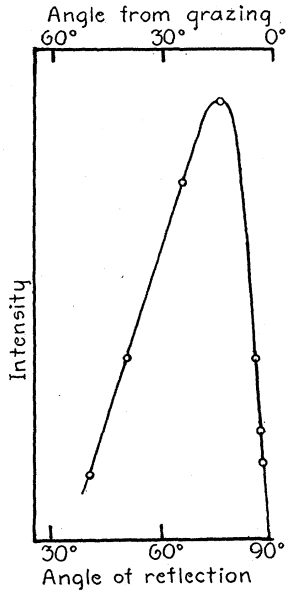

Fig. 7. Angle of incidence 46°. Initial energy of potassium ions 40 volts.

The position of the specular angle was accurately determined by turning the collector until the light from the glowing source after reflection from the target fell on the hole in the shield enclosing the collector. At this angle the intensity in Fig. 7 is seen to be small. It seems likely that if a smoother target could be used, the intensity would be found to fall still more suddenly to zero at the grazing angle.

The absence of specular reflection is obvious when we measure the intensity on either side of the meridian plane. Curve 1 in Fig. 8 shows the intensity on either side of the meridian when the collector had been set at the specular angle. The scattering extends through the whole 180 degrees. It is clear that when the collector is below the horizontal, i.e. when the collected beam makes more than a right angle with the incident beam, par-

ticles can no longer be collected through 90° on either side of the meridian. For at a smaller angle than this the collector will pass below the plane of the target, and disappear below the horizon. Thus the curve 2 in Fig. 8 is of necessity restricted, this curve having been taken through the peak in Fig. 7. The curves in these Figs. 7 and 8 are the only curves in this paper taken with the simple apparatus; the rest were all taken with the positive ray box.

Adsorbed layer on a cold target. Suppose that with the positive ray box we make a setting on the top of a peak, (by which we mean set the value of the electric field between the slits to bring the maximum yield to the Faraday cylinder). If we then turn off the heating current through the target, the

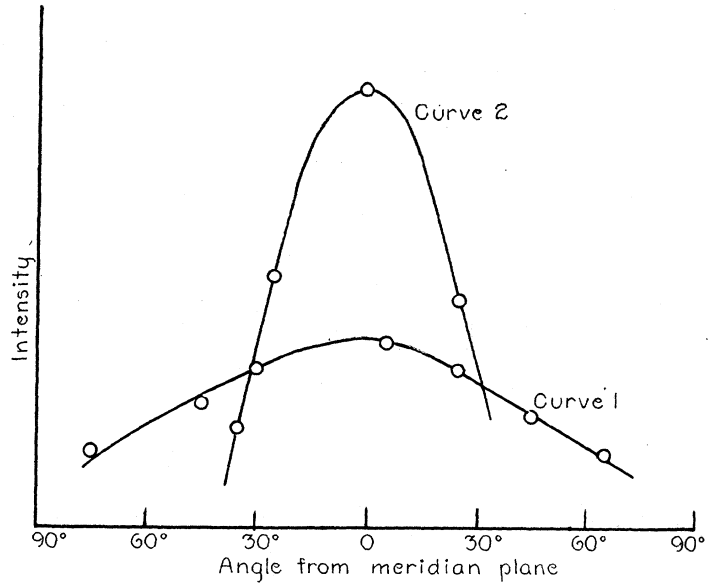

Fig. 8. Angle of incidence 46°. Initial energy 40 volts. Curve 1. Angle of reflection 44°. Curve 2. Angle of reflection 77°.

number of ions immediately falls off as shown in Fig. 9. Read took his measurements a few seconds after turning off the heating current, and states that the results were approximately the same as for a hot target. This was presumably because his method did not pay attention to the velocity of the scattered ions. For the rapidity of the fall in the first few seconds is due partly to the rate of decrease in the number of ions scattered, and partly to their rapid decrease in energy, which prevents them from traversing the magnetic field to the Faraday cylinder.

Curves similar to those in Figs. 3, 4, and 6 were obtained with an adsorbed layer, except that in this case the intensity was about one-eighth of that from a heated target, and the energy retained by the ions about one-half; i.e. the energy retained rose to 40 percent of their initial energy near grazing in-

cidence, instead of about 80 percent. Read stated that with his apparatus a cold target became after a few minutes completely ineffective as a reflector.

We will consider the rate of contamination first by potassium and then by residual vapour. The number of ions in one microampere is less than 10^{13} per second. The number of ions passing through the slit and reaching the target must have been less than 10^{10}. If the atomic radius is 10^{-8} it will require 10^{16} atoms to form a unimolecular layer over unit area, or 10^{15} atoms to cover one-tenth of this area. It is clear that the formation of a layer of alkali from the beam of incident ions would be extremely slow, even if a large proportion of them adhered to the cold target.

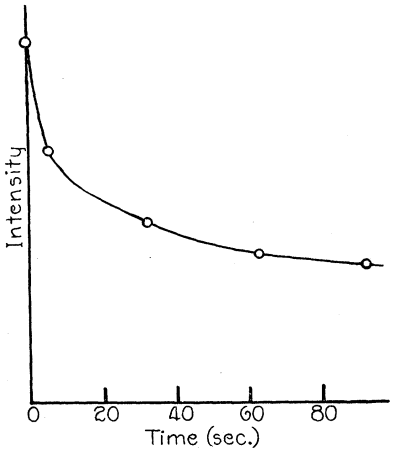

Fig. 9. Abscissae show the time elapsed since the heating current through the target was cut off.

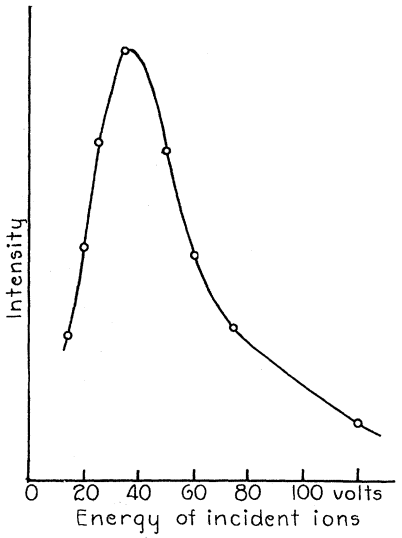

Fig. 10. Angle of incidence 67° Angle of reflection 66°.

By means of an ionization-gauge attached to the tube it was found that the pressure of residual vapour (presumably from the two greased joints) was about 10^{-4} mm, which means about 10^{12} molecules per cc. The number of molecules striking unit area per second is $nv/3$, where v is their temperature velocity; this comes to about 10^{16} per second. So that if it were one molecule out of every hundred hitting the surface that was adsorbed, a unimolecular layer would be formed in a few minutes.

Critical energy for intense scattering. Returning to the scattering from a heated target, we have seen from the curves in Fig. 6 that the intensity varies greatly with velocity of the incident beam. Fig. 10 shows the type of curve obtained by varying the energy of the incident ions for given angles of incidence and reflection. Very similar curves, showing a sharp maximum at about 40 volts were obtained for caesium and lithium. Almost identical curves were obtained with each apparatus. In those taken with the first each

point represents the area of a positive ray peak; in the second it represents a direct reading from the electrometer, the integration over velocities having been made by the apparatus. The position of the maximum is nearly independent of the angle of incidence or reflection.

Read obtained a curve for lithium with a maximum intensity at about 48 volts, but as his measurements were confined to the meridian plane, it was not clear whether the scattering was greater in all directions at 48 volts, or whether the ions were more concentrated on the meridian at this voltage. The scattering at higher and lower voltages might have been not less intense, but more diffuse. But we have found that at different voltages the scattering on either side of the meridian is equally diffuse.

The question immediately arises as to what becomes of the ions which are not scattered. They may (1) pick up an electron as they collide with the surface and be reflected neutral. (2) They may be adsorbed and reemitted later either neutral, or as an ion with very small energy. (3) They might accumulate on the surface, even at a red heat, their charge being neutralized by an influx of electrons into the target.

It is well known that platinum at an intense red heat emits alkali ions. In fact it was found that when the negative end of the target was connected to the upper slit of the positive ray box, (thereby making the target slightly positive with regard to the slit owing to the potential drop of the heating current) a copious positive ion current could be obtained at an intense red heat. In the final measurements the other end of the target was accordingly connected to the slit, and there was therefore a retarding field of a volt or less which would keep very slow ions out of the positive ray box. If therefore the non-scattered ions were adsorbed and reemitted with small thermal velocities, they would not have been collected, whether charged or neutral. This argument, however, does not seem to apply to Read's case.

Discussion

According to the wave mechanics a particle of mass m and velocity v is associated with a wave of wave-length h/mv. For the ions used in these experiments the wave-lengths are found to be of the order of 0.01 Angstrom. They correspond to gamma-rays, and it is difficult to predict what effects would be expected.

If we try to account for the results by multiple collisions between the ions and the atoms at the surface of the target, difficulties are encountered. At first sight, however, the phenomena appear to be qualitatively what would be expected from collisions between free particles. Thus it has been shown: (a) the least deviated ions retain the most energy, (b) the intensity is concentrated in a forward direction, the number of particles which are deflected through large angles being small, (c) the ions scattered from light atoms (adsorbed layer) give up a greater fraction of their energy than those scattered from heavy atoms (heated platinum).

On the other hand, when we consider it in detail we do not find agreement. Let V be the initial and v the final velocity of an ion of mass M, and let m

be the mass of a free atom with which it collides. Then if the ion is deflected through an angle ϕ, the velocity after a single collision is

$$v = V\{M\cos\phi \pm (m^2 - M^2\sin^2\phi)^{1/2}\}/(M+m)$$

We find that a platinum atom is so much heavier than potassium or lithium, that an ion can lose very little energy except in the case of the large deviations which are very improbable. Yet if the large losses of energy are the result of collisions with many atoms, why is the beam of ions scattered at a given angle so homogeneous? The difficulties are equally serious in the case of the layer adsorbed on a cold target, since this presumably consists mainly of carbon and oxygen atoms, which are so light that they can give the potassium ion only very small deflections. Thus $(m^2 - M^2\sin^2\phi)$ becomes negative when ϕ is greater than 18°; and the most probable deflection must be less than this, since the condition for maximum deflection is rare.

Finally there is the critical energy for intense scattering, the same for caesium, potassium, and lithium. The velocity and momentum of caesium and lithium ions having the same energy differ by a factor of 4.3, since they depend on the square roots of the masses. It has been pointed out that to interpret this maximum one needs evidence as to what becomes of the ions which are not scattered. Work is being continued in the hope of eliminating grease vapour from the tube, and of using a crystalline target.

In conclusion I wish to express my thanks to Professor K. T. Compton for extending to me the privilege of working in the Palmer Laboratory and for his interest in this work; to Professor H. D. Smyth for helpful discussion; and to the International Education Board, to whose grant of a fellowship my visit to America was due.

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PRINCETON UNIVERSITY.
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